



High Ice Water Content Flight Campaign

Thomas Ratvasky

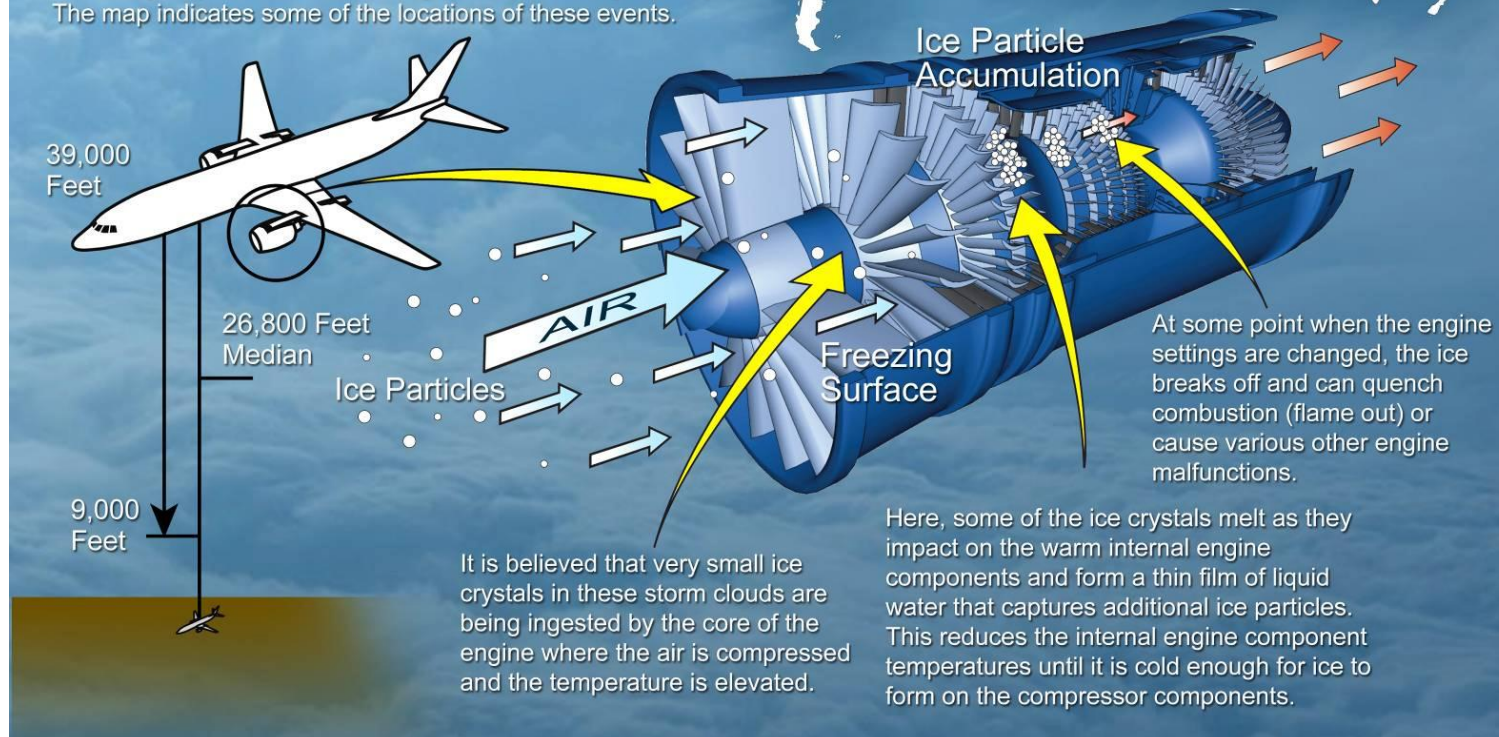
2011 Annual Technical Meeting
May 10–12, 2011
St. Louis, MO

Engine Power Loss Description



The Dangers of Jet Engine Icing

Flight into certain types of storm clouds can cause ice to build up inside the core of jet engines and cause temporary shutdowns. There have been 108 engine power loss events identified since 1988 - fourteen of these were multi-engine flameouts. Even though pilots are using storm avoidance guidance, engine power loss events are continuing to occur on a variety of airplane and engine types. No accidents are known to have occurred from iced engine power loss - engine power loss was temporary in all cases but one, where an emergency "dead-stick" landing was successfully accomplished. The map indicates some of the locations of these events.



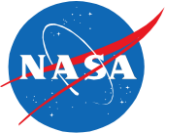
Statement of Need



- Over the past 10+ years, it has been recognized that jet engine power-loss events occur around deep tropical convection at higher altitudes.
 - Theorized that flights were in areas of high concentrations of ice crystals
 - Power-loss results from ice crystals entering the engine core, melting and refreezing inside the engine
 - Engine Harmonization Working Group proposed new certification criteria; FAA issued Notice For Proposed Rulemaking; Rule to take effect 2012
- NASA, together with partner organizations*, have proposed a field campaign using an instrumented research aircraft to characterize this environment.
 - Darwin, Australia ideal for this purpose during monsoon period which occurs between December and March.



*** FAA, Boeing, Environment Canada, Australian Bureau of Meteorology, National Research Council of Canada, National Center for Atmospheric Research, Airbus, and Transport Canada.**



What Will the Flight Campaign Deliver?

- Flight campaigns to characterize the HIWC environment are being organized by NASA, FAA, Environment Canada, Boeing, Australian Bureau of Meteorology, NRC Canada, NCAR, and others
 - The overarching goal of the HIWC flight campaign is to acquire a **benchmark database** of the atmospheric environment that causes engine and air data sensor failures that threatens air transportation safety

Set new design and certification standards for engines and sensors to operate within this environment

Develop HIWC detection methods (onboard, ground-based, space-based) and weather diagnostic & forecast tools to enable threat avoidance

Develop engine ice models/simulations and guide future experimental activities for means of compliance & fundamental ice growth studies

Understand the fundamental cloud microphysical processes that cause High IWC to occur and, by doing so, improve the ability to forecast or detect it



High IWC Field Campaign Overview



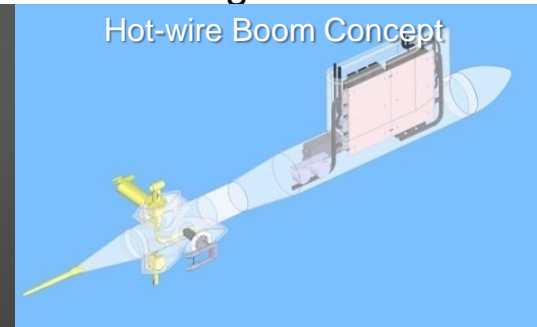
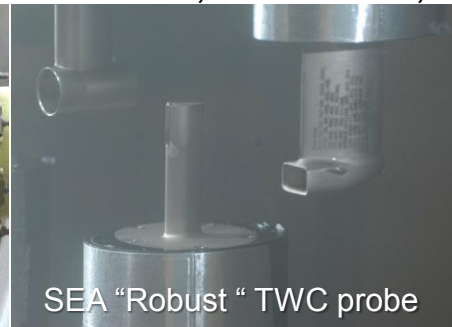
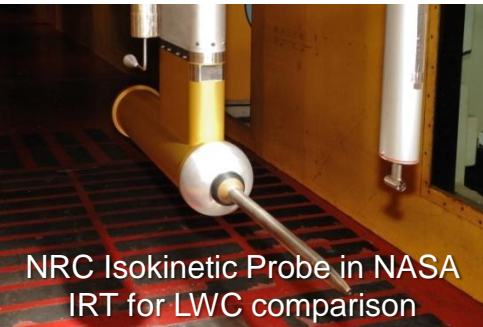
- Develop, modify, test cloud physics instruments for use in HIWC conditions
- Setup contract for Aircraft Services to Conduct High Ice Water Content (HIWC) Flight Research
- Modify the research aircraft
 - Design, integrate and test systems and instrumentation for data collection
- Conduct a “Trial” Campaign in Darwin, Australia (2012)
 - for instrument testing in a tropical environment and to test sampling strategies; develop findings/lessons learned
- Review findings
 - fix instruments; update test plans
- Conduct Primary Field Campaign in Darwin, Australia (2013)
 - to acquire data to meet engine and science related objectives



HIWC Instruments

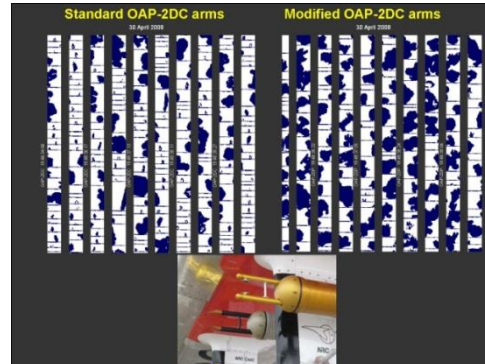
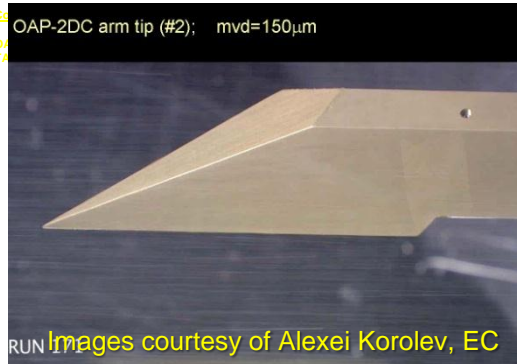
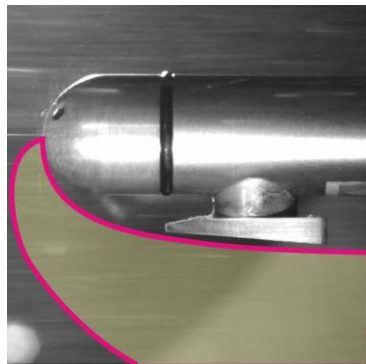
Instruments for HIWC Field Campaign

- Total Water Content (TWC): mass of water (liquid + ice) in volume of air
 - Most critical parameter; challenging to measure in high concentrations of ice; redundancy required
 - Issues:
 - Saturation: mass concentrations up to 9 g/m^3 are theoretically possible
 - Under-sampling do to particle bounce, break up, shedding
 - Ice crystals can be erosive to small hot-wires used for water content measurement
 - Actions Taken:
 - NRC Canada and Environment Canada developed an Isokinetic Evaporator Probe to measure TWC up to 10 g/m^3 at 200 m/s
 - Science Engineering Associates (SEA) modified at TWC probe to be “Robust” and increased saturation limits; developed Hot-wire Boom
 - Nevzorov LWC/TWC probe sensors modified for HIWC conditions
 - Instruments tested in NRC M-7 tunnel, NASA IRT, and Cox Icing Tunnel



Instruments for HIWC Field Campaign

- Cloud & Ice Particle Concentration, Size, Shape:
 - Second most critical parameter; helps understand cloud growth processes; and ground facility simulation requirements
 - Issues:
 - Measurement particle artifacts due to ice particle shattering on probe tips
 - Probe electronics disabled due to electro-static charge caused by high speed, ice crystal impacts
 - Optics fogging in high humidity tropical air after cold soaking at altitude
 - Actions Taken:
 - EC designed and tested new probe tips to reduce artifacts
 - Titanium Nitride (TiN) conductive coating on probes sensitive to electrostatic buildup
 - Dry air purge system defined to keep optics clear; manage condensation within probes



Instruments for HIWC Field Campaign



Measurement Type	Instruments/Probes
Water Content	NRC Isokinetic Evaporator , Hot-wire boom with SEA “robust” probe , Nevzorov LWC/TWC probe , SEA LWC probe, King LWC probe;
Cloud Spectrometers	PMS Forward Scattering Spectrometry Probe , DMT Cloud Droplet Probe , SPEC 2D-S , SPEC Cloud Particle Imager , PMS Optical Array Probe 2D-C , DMT Cloud Imaging Probe , PMS Optical Array Probe 2D-P
Atmospheric State	AIMMS-20 wind/gust probe , Goodrich total air temperature (TAT), UK Solid Wire TAT, LICOR water vapor, Buck Research CR-2 hygrometer, Edgetech Model 137 hygrometer, MayComm TDL open path hygrometer
Light Extinction	EC Cloud Extinction Probe
Ice Detection	Goodrich 0871LM5 ice detector, Goodrich 0871FA ice detector,
Remote Sensing	Honeywell RDR-4000 pilot weather radar, Ka-band cloud profiling radar, L3Com WX-500 Stormscope
Imaging & Audio	High Def and Standard Def cameras, video annotator, HD and SD recording decks to capture windscreen, research instruments, engine inlets
Aerosols	TSI Condensation Nuclei (CN) counters, Scanning Mobility Particle Sizer
Aircraft & Engine Data	Airspeed, altitude, position, heading, roll, pitch angle, vertical acceleration, engine N1, N2, TGT, throttle position

Note: red font indicates new or modified for HIWC



HIWC Aircraft

Aircraft for HIWC Field Campaign

- Competitive RFP led to selection of Flight Test Associates to provide a Gulfstream G-II aircraft to be modified and flown in HIWC campaigns
- HIWC G-II Features
 - Modified G-II estimated range: 2755 nm; Endurance: 6 hours; Ceiling: 37-41 kft
 - RVSM and Stage 3 hush kit
 - Engines: Rolls-Royce Spey Mk 511-8; no history of engine power loss events
 - Sufficient volume in cabin for research equipment and operators
- FTA has experience with modifying and testing G-II aircraft for similar installations in timely manner



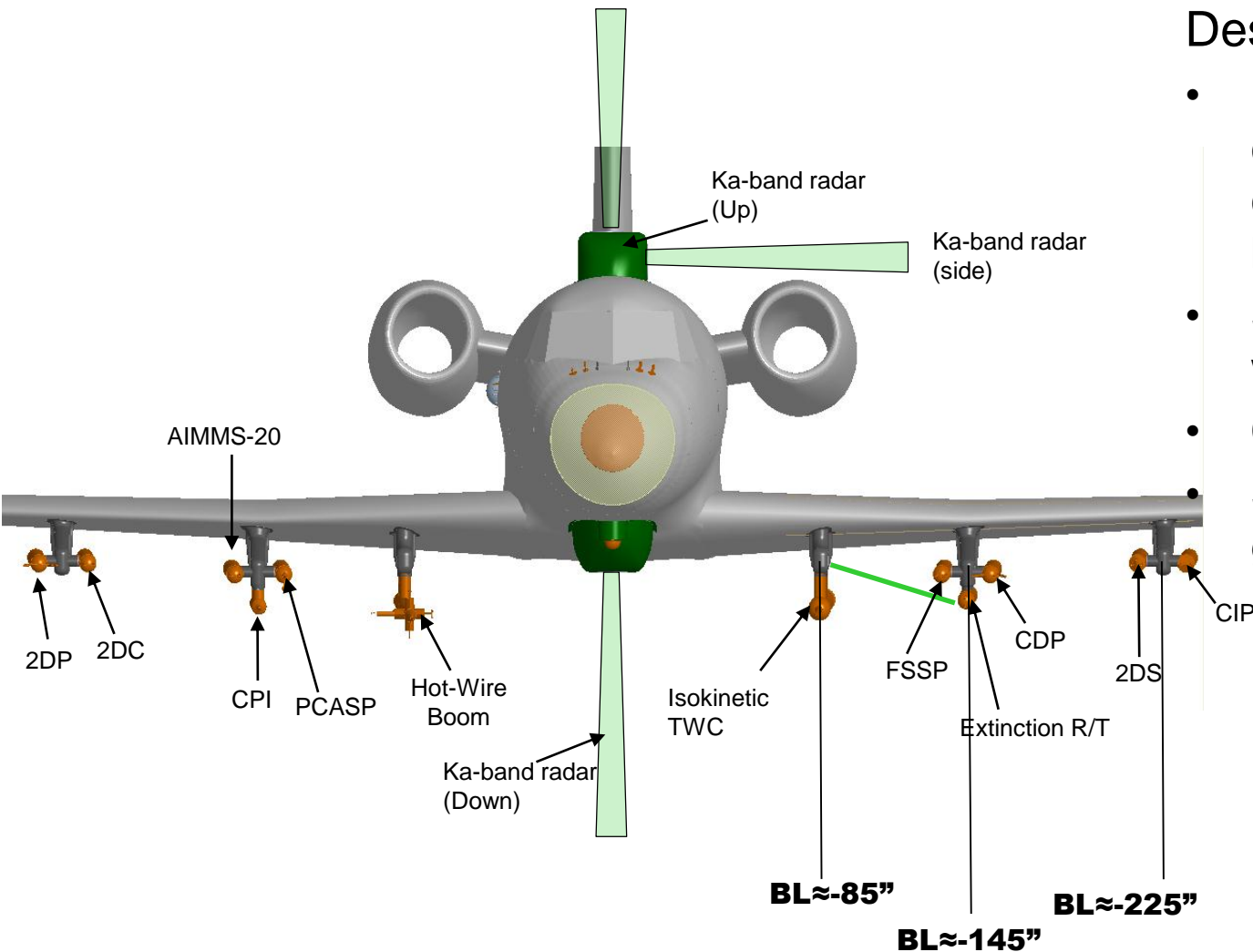


Aircraft for HIWC Field Campaign

- Aircraft leased to Flight Test Associates from Threshold Aviation Group and available to HIWC team for duration of contract
- Aircraft will be operated as a public aircraft and follow NASA airworthiness procedures
 - NASA will maintain operational control of all flights
 - NASA design and safety processes will be used to assure airworthiness
 - FTA/Threshold pilots will be PIC
 - NASA pilots have received Gulfstream type ratings and will be safety observers / SIC for all flights



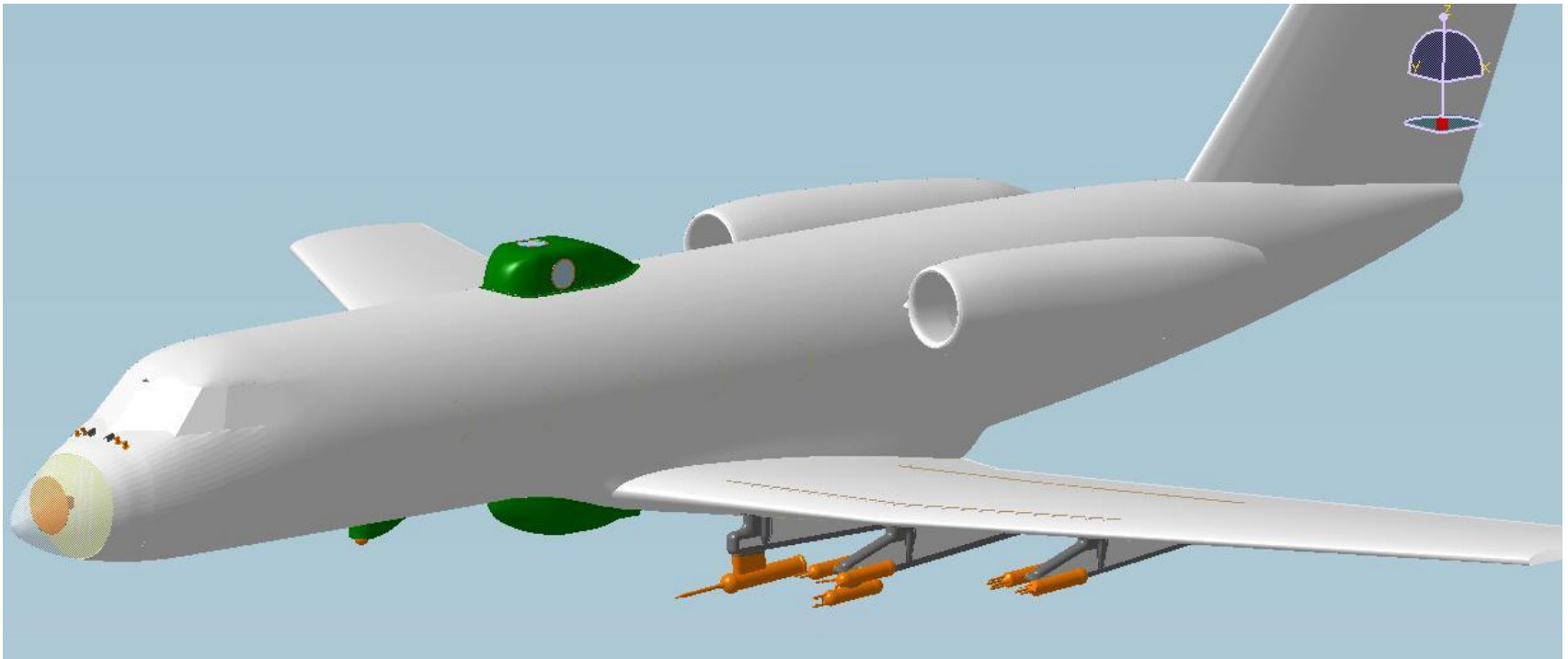
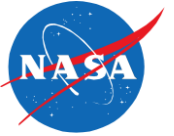
Aircraft for HIWC Field Campaign



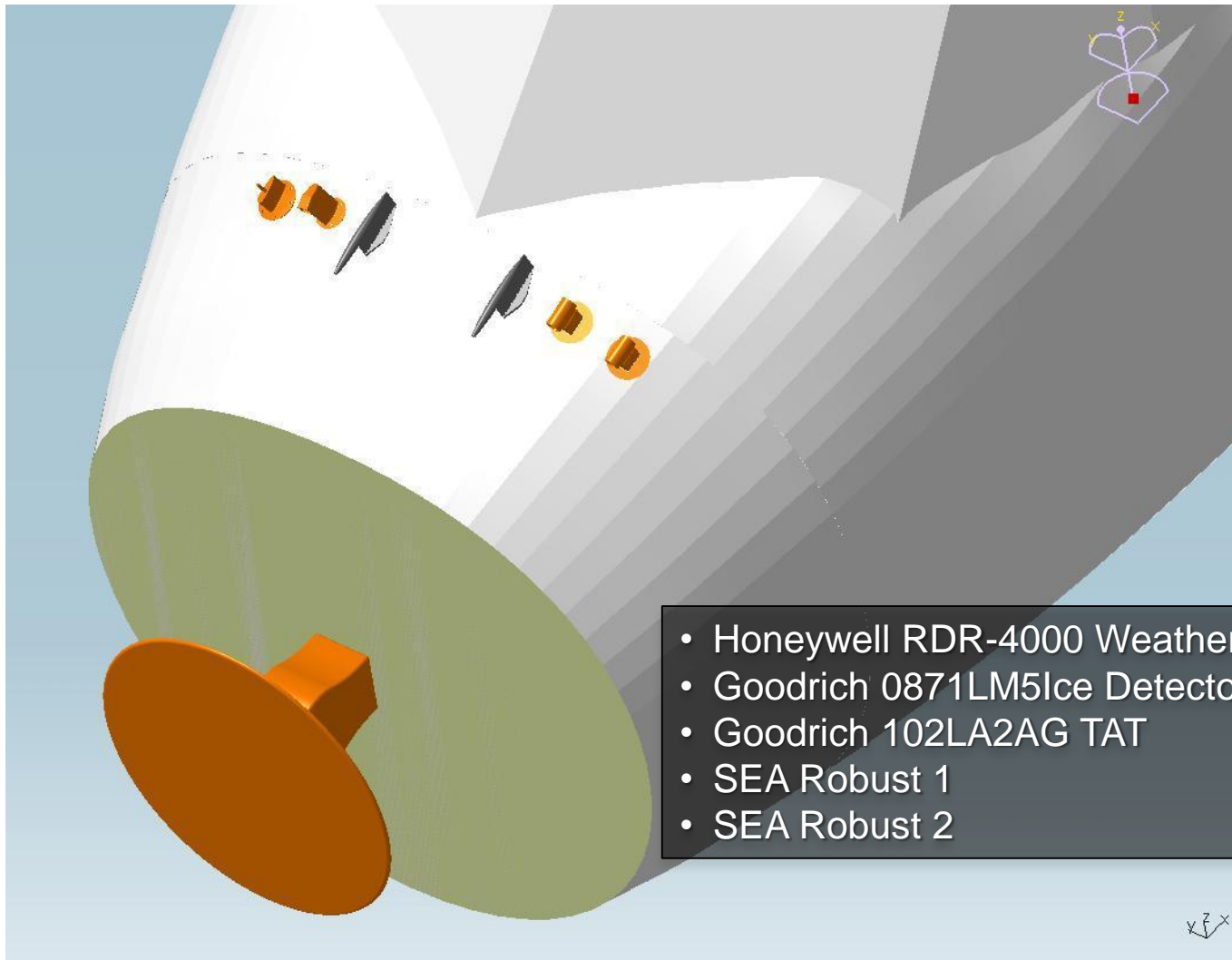
Design Mods Underway:

- Probes to measure cloud properties that cause engine power loss events
- State of Art pilot weather radar
- Cloud profiling radar
- SatCom for data link to ground base

Exterior Aircraft Instrument Locations

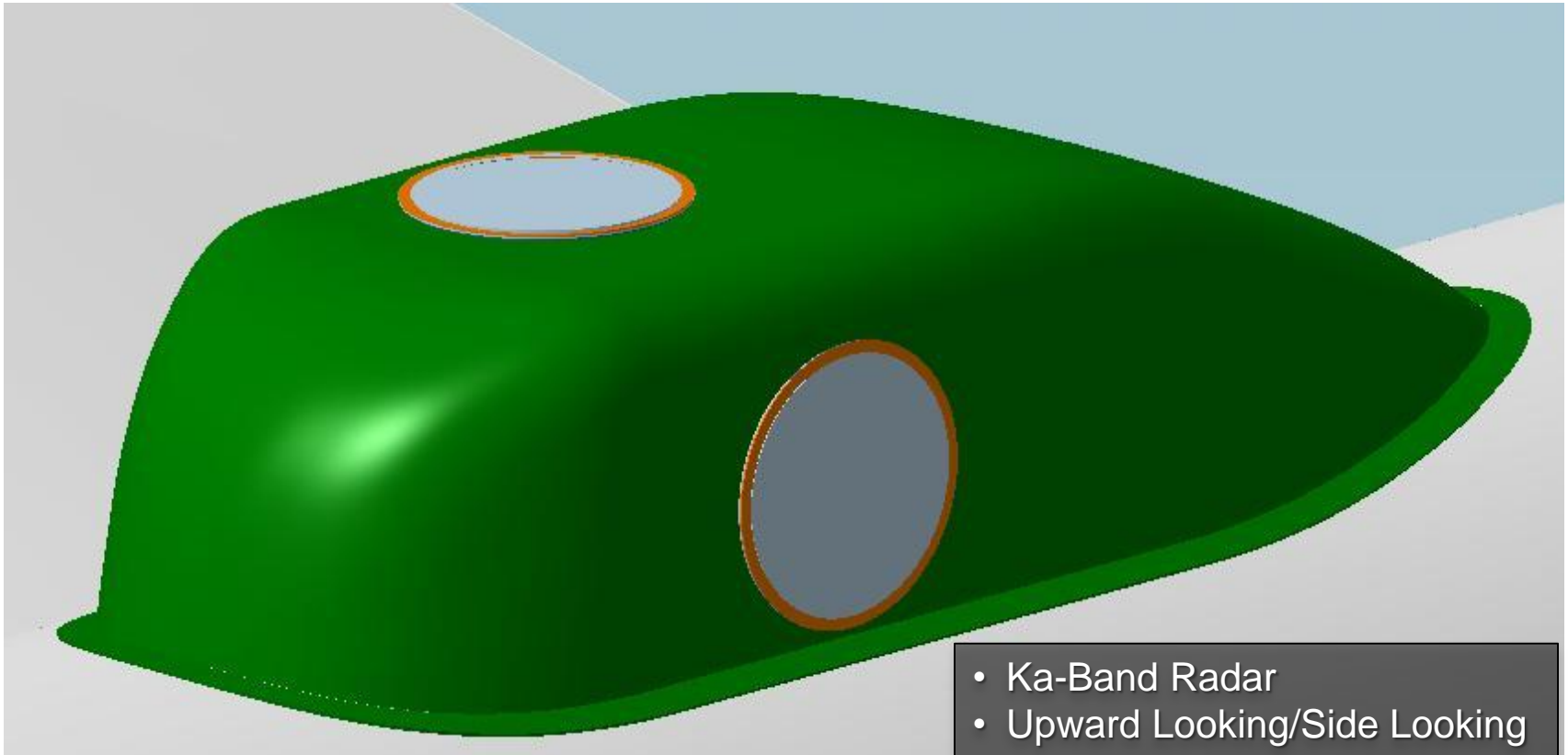


Exterior Aircraft Instrument Locations: Nose



- Honeywell RDR-4000 Weather Radar
- Goodrich 0871LM5Ice Detector
- Goodrich 102LA2AG TAT
- SEA Robust 1
- SEA Robust 2

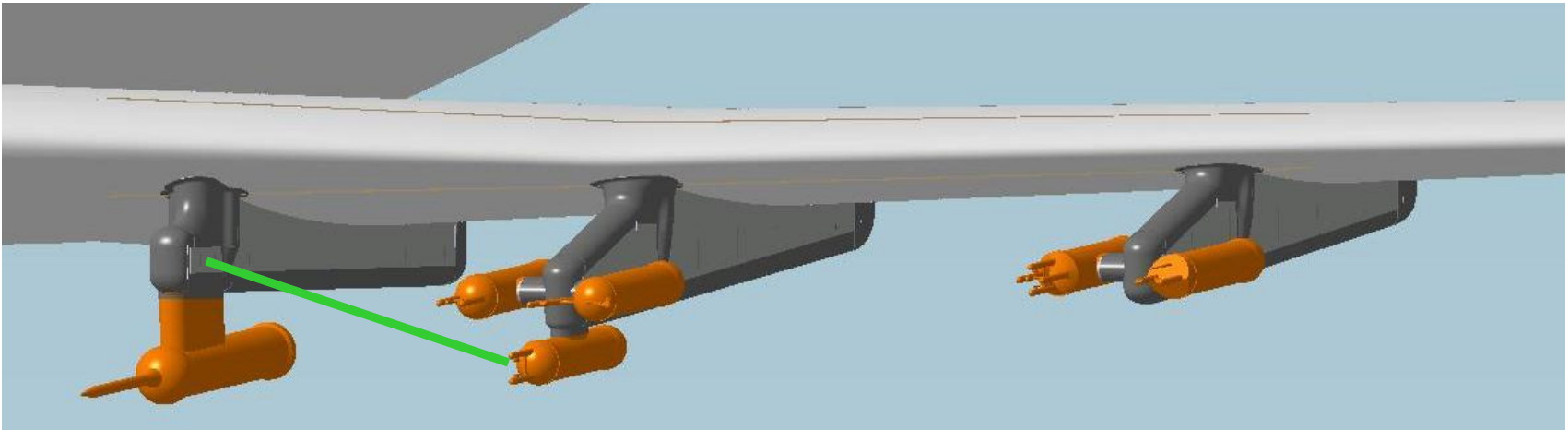
Exterior Aircraft Instrument Locations: Ka-band Radar



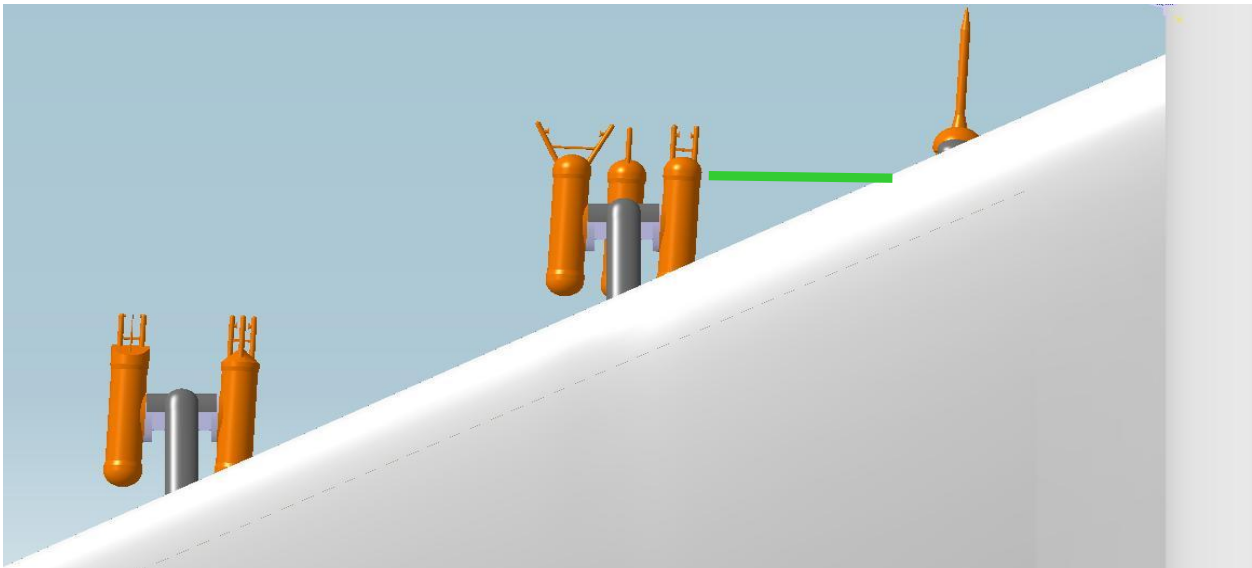
Exterior Aircraft Instrument Locations: Left Wing



Exterior Aircraft Instrument Location (Left Wing - Iso View)



Exterior Aircraft Instrument Location (Left Wing - Top View)

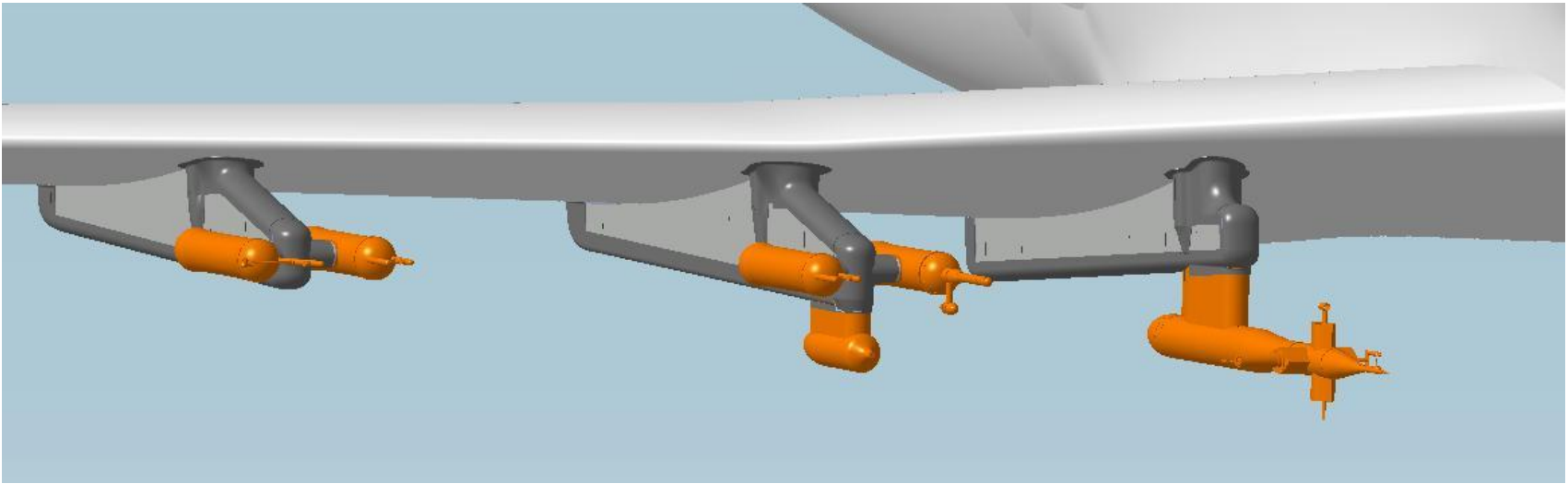


- Isokinetic Probe
- FSSP
- Extinction Probe
- CDP
- 2D-S
- CIP

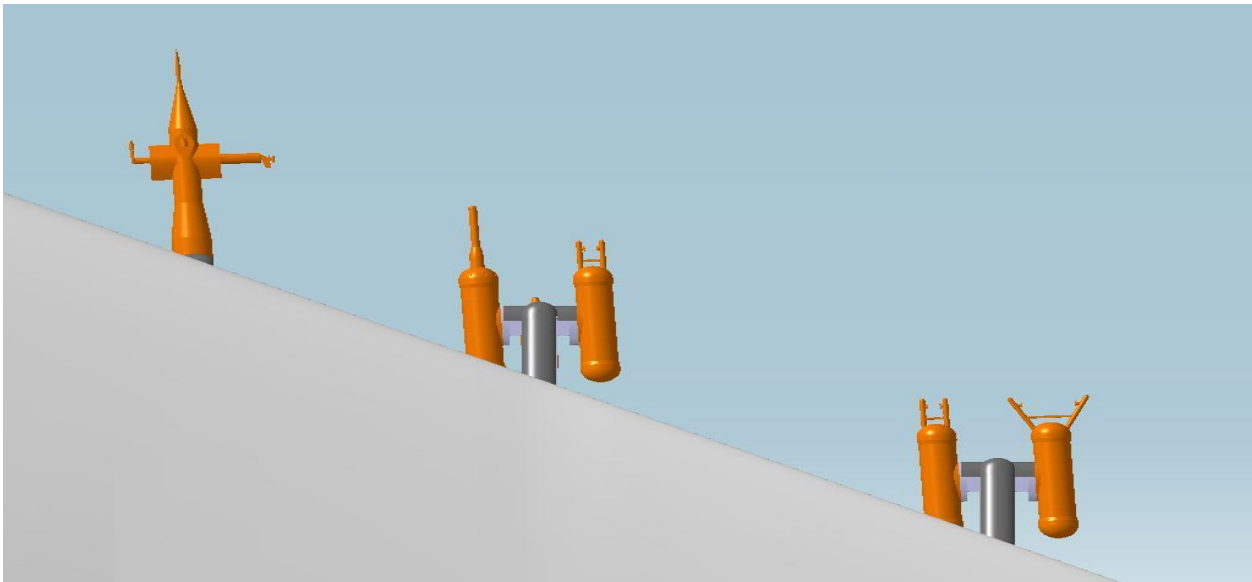
Exterior Aircraft Instrument Locations: Right Wing



Exterior Aircraft Instrument Location (Right Wing - Iso View)

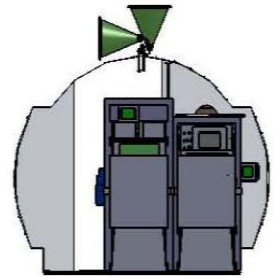
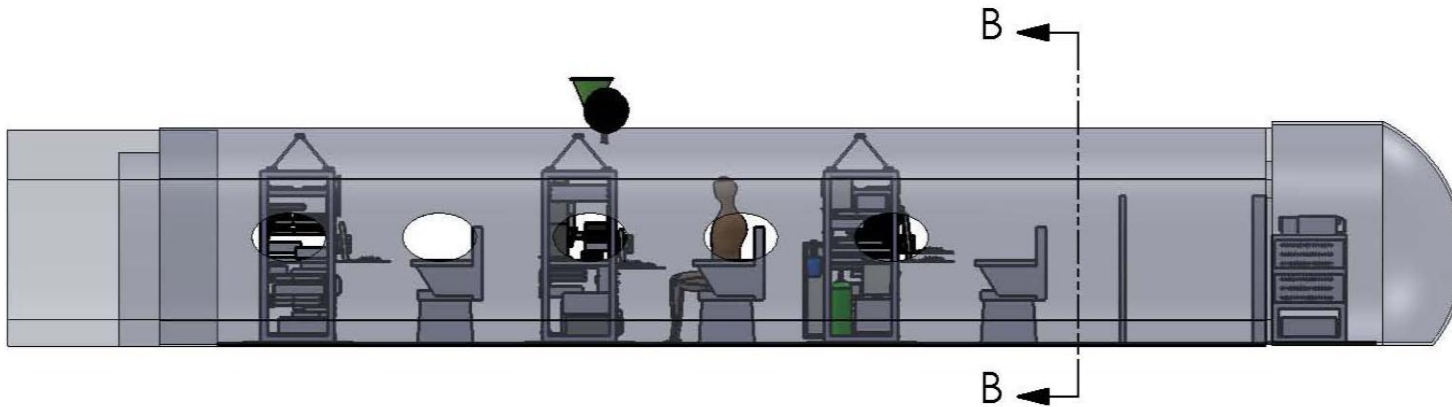
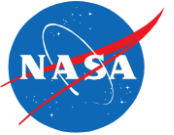


Exterior Aircraft Instrument Location (Right Wing - Top View)

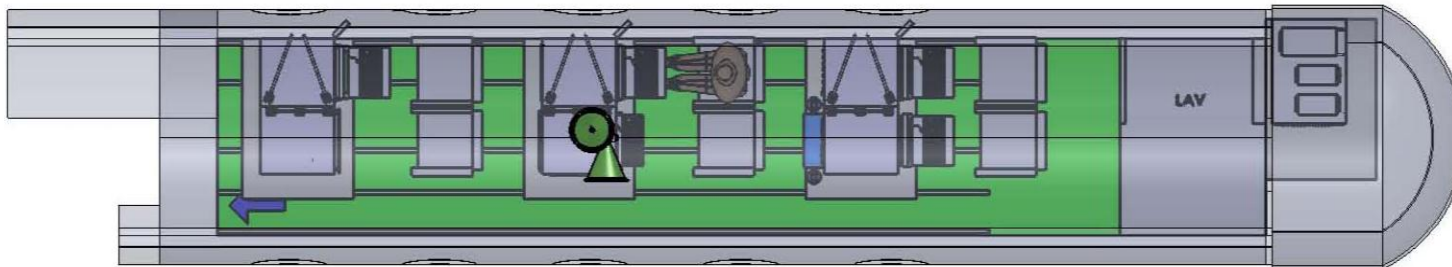


- Hotwire Boom
- AIMMS-20
- CPI
- PCASP
- OAP-2D2C
- OAP-2DP

Research Racks & Stations



SECTION B-B
SCALE 1 : 42





HIWC Campaigns

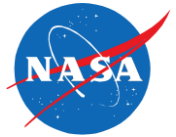
Why Darwin?

HIWC Database best acquired at Darwin, Australia

- Austral summer season (Dec-Feb) has a high frequency of occurrence of the types and scales of convective storms to sample
 - Monsoon – large scale, oceanic convection
 - Break – continental convection in between monsoon events
- Ground-based observing systems in Darwin are unparalleled anywhere in tropics and offer context for the HIWC research aircraft measurements
- The Australian Bureau of Meteorology providing ground-based observing systems and expertise as in-kind contributions
- Large number of engine-events occurred over Southeast Asia and Australasia
- A significant number of field programs have been conducted from Darwin including 1950's RAE effort to characterize ice crystal atmosphere



Trial Campaign (Darwin, Australia)



- Objectives
 - Operate the HIWC research aircraft in a tropical environment to verify HIWC instrumentation operability before the primary data collecting campaign
 - Operate the HIWC research aircraft in Darwin to gain operational knowledge, verify engine operations in HIWC conditions, and verify communications and logistics processes to minimize project risk for primary campaign
 - Operate the HIWC research aircraft in a tropical environment to test sampling strategies that are proposed in the science plan
- Timeframe:
 - 3-4 weeks in Feb-March, 2012
- Outcome:
 - Develop findings/lessons learned
 - Address these before Primary Campaign





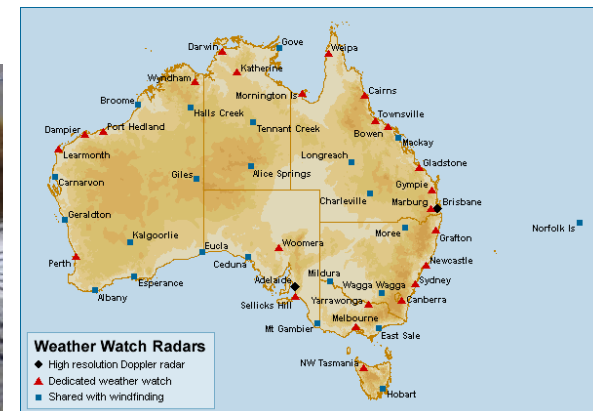
Primary Campaign (Darwin, Australia)

- Objectives
 - Engine-related:
 - Characterize High IWC Environment: 99-percentile stats on TWC
 - Develop detection methods for High IWC
 - Develop diagnostic and forecast tools for High IWC environment
 - Science-related:
 - Characterize microphysical properties (ice water content, particle size distributions and shape) of deep convective clouds
 - Determine small ice particle formation mechanisms
 - Determine the temporal and spatial evolution of mixed phase (supercooled liquid and ice crystals) in deep convection
 - Improve understanding of precipitation formation mechanisms and precipitation efficiency
 - Validate ground-remote sensing of microphysical properties of deep convection
 - Improve simulations of deep convection using Cloud Resolving Models
 - Validate satellite-remote sensing of cloud properties and high IWC regions in deep convection



Primary Campaign (Darwin, Australia)

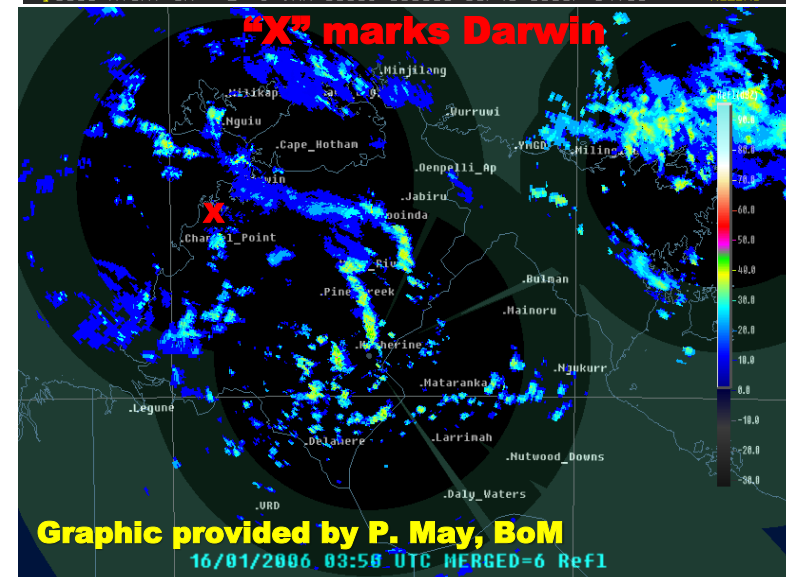
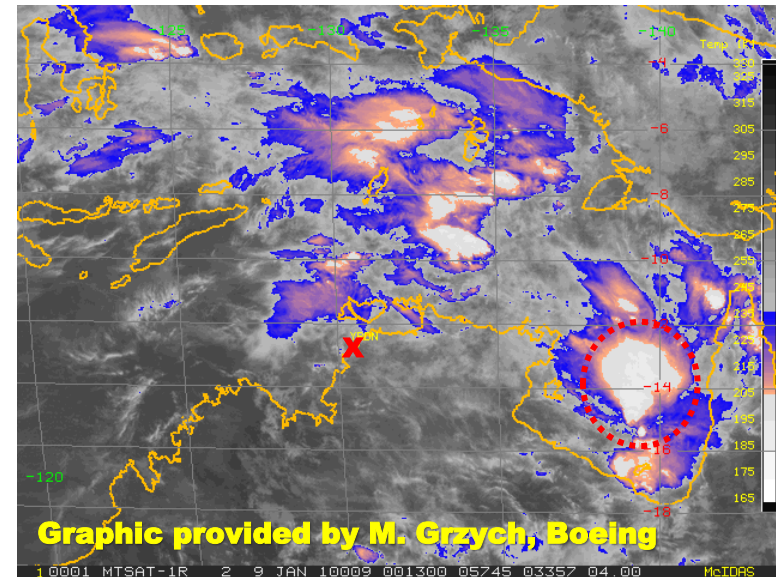
- Timeframe:
 - Up to 10 weeks during “wet season” (Jan-Mar, 2013)
- Estimate 140 research flt-hrs required to obtain 99%-stats for 20 mile reference scale-length at 3 altitudes
- Facilities:
 - RAAF base Darwin
 - BOM NT Regional Office, forecast operations center
 - Operational radars
 - BOM C-POL radar
 - Geostationary Satellites: MTSAT (hourly), Korea – COMS1
 - DOE ARM site



Primary Campaign (Darwin, Australia)



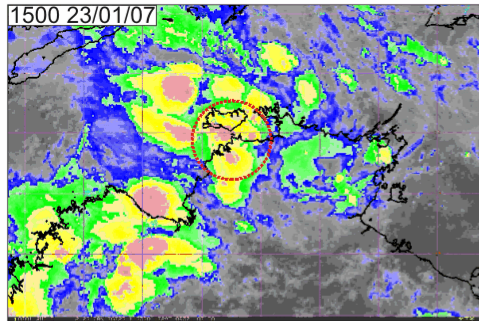
- Types of Deep Convection to be Sampled
 1. Oceanic, meso-scale convective systems (MCS) to get long transects if available
 2. Oceanic (smaller storms) if MCS not in operating area
 3. Continental (break) convection when monsoon moves out of area



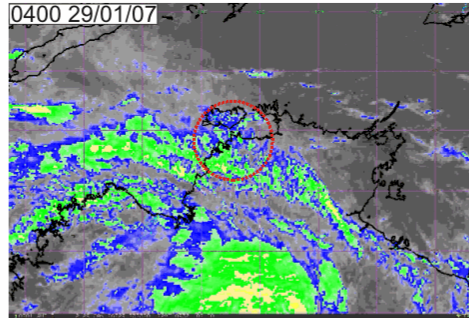
Primary Campaign (Darwin, Australia)



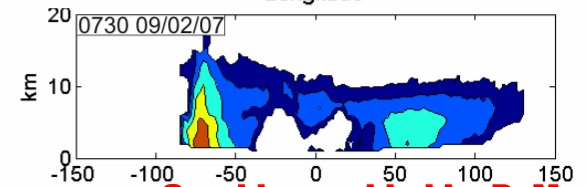
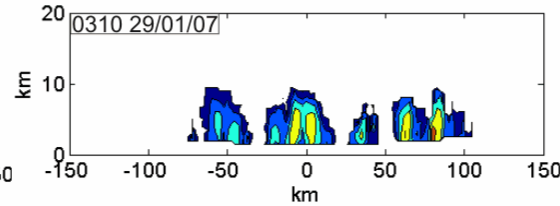
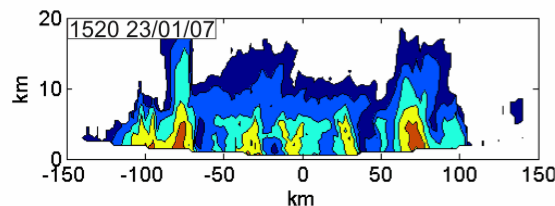
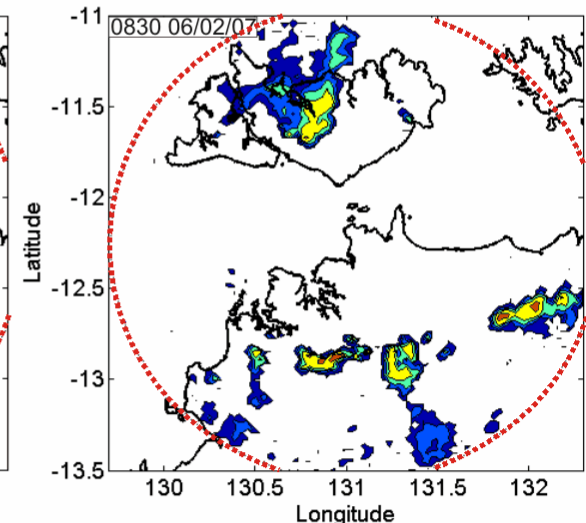
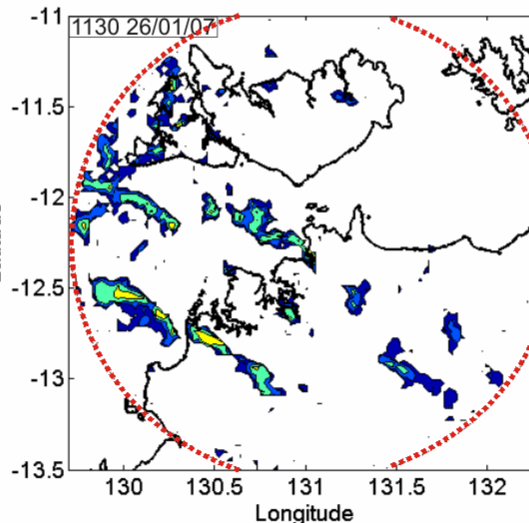
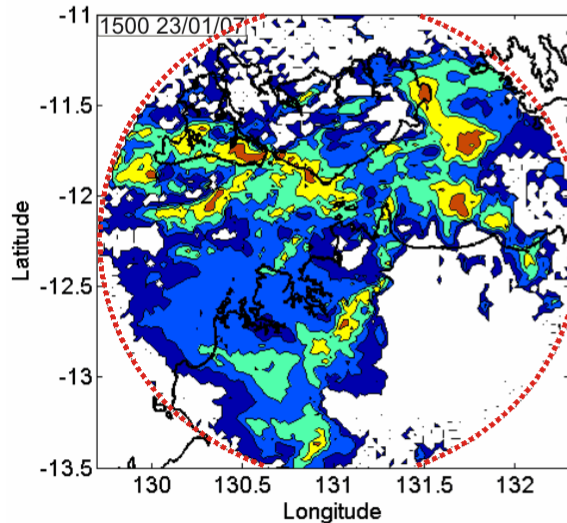
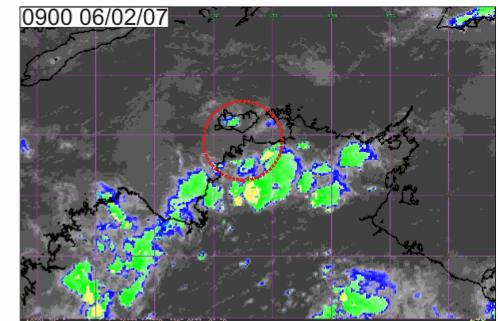
Active Monsoon



Suppressed Monsoon



Break

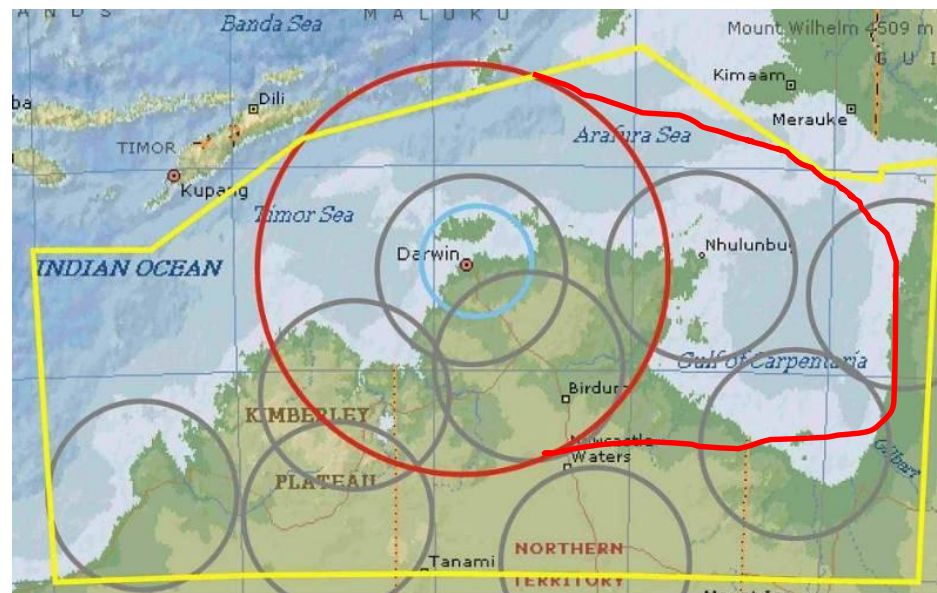


Graphic provided by P. May, BoM

Operational Area



- All flights within yellow boundaries
 - Australian Airspace
- Three primary flight altitudes:
 - -50 C (± 3 C), approx 37kft
 - -10 C (± 3 C), approx 22 kft
 - -30 C (± 3 C), approx 30 kft
 - Require 100, 20-mile flight legs at each altitude.
- Flights within CPOL radar (blue ring) for continental (break) convection
- Stress flights within radar coverage (grey rings)

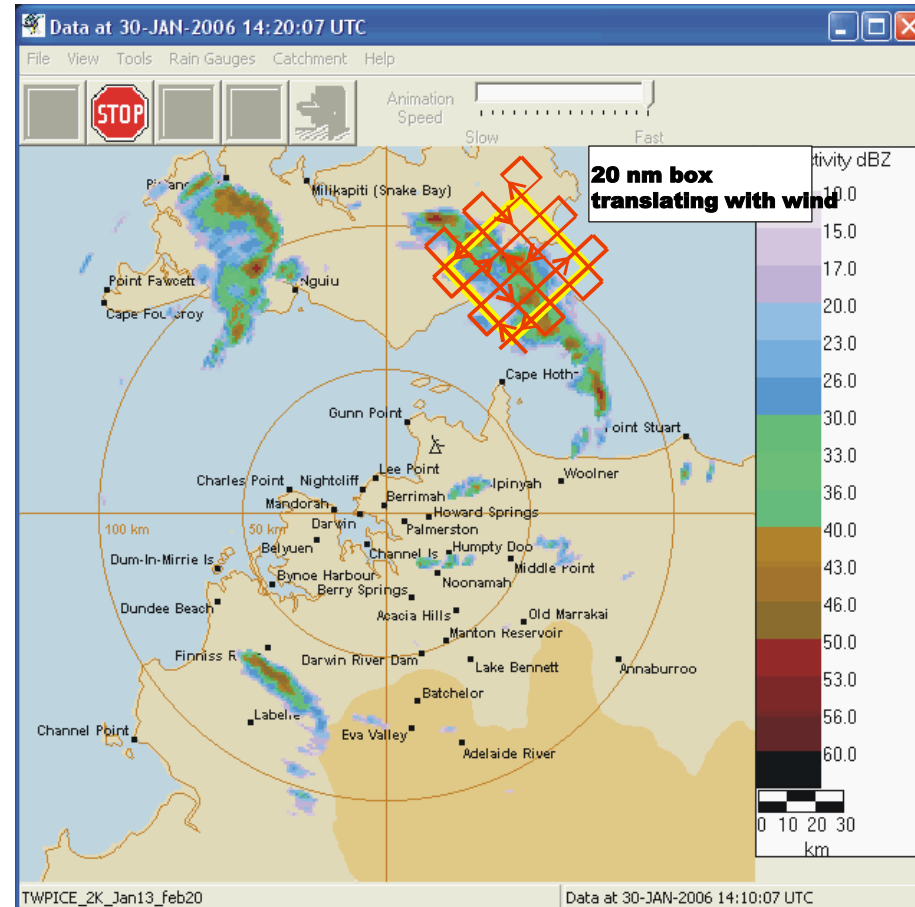


Modified G-II estimated range: 2755 nm; 6 hours

Sampling Strategies: Oceanic



- Pick area of expected high IWC above a region of heavy rain below (ground radar), or from overshooting tops (see Science Plan)
- 20 nmile sided box oriented with one side down axis of expected updrafts
- Collect repeated runs to build up statistics of 20 mile average TWC (and lower)
- Pattern also meets many of the meteorological science objectives
- Statistics produced conditional on being within 20 miles of storm



Sampling Strategies: Continental

- more vigorous – possible hail/lightning
- Previous experiments with more delicate aircraft (e.g. Egrett, Proteus) have only worked the trailing stratiform anvil region, or low-altitude feeder cells on upwind side
- Propose to work from the outside in, as deemed safe by pilots, and outside yellow and red-echo regions - work decaying clouds
- May not be conducive to 20-mile statistics, and multiple altitudes
- Oceanic ‘bread and butter’ of sampling

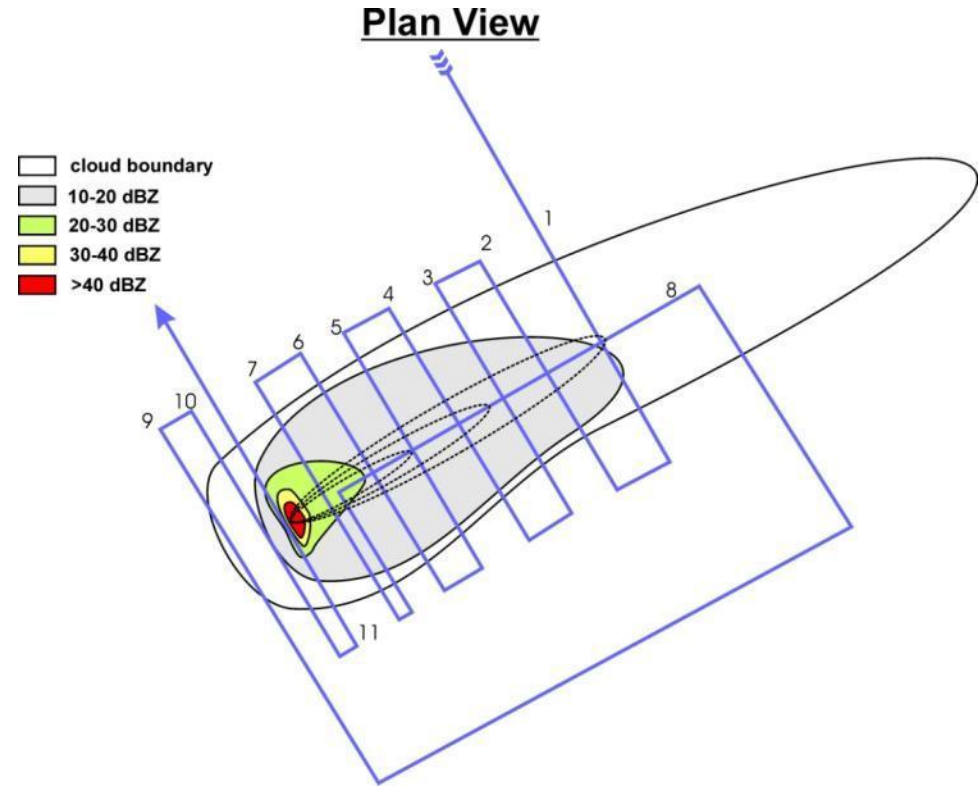


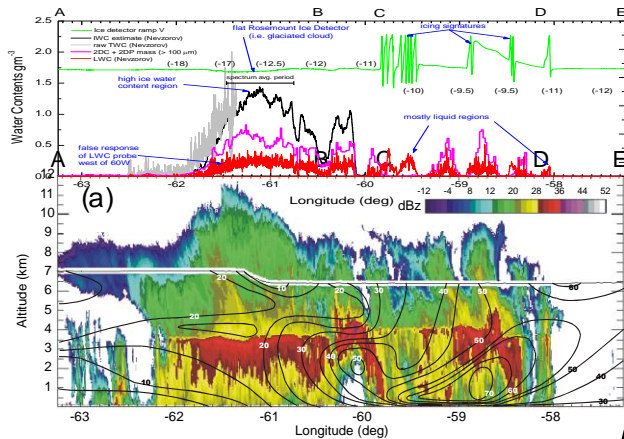
Figure 7.3: Idealized flight plan for isolated single-cell continental convection case.

Operational Concept



- Pre-flight Briefings (~03:30-06:00)
 - Weather: identify potential storms, locations, timing, altitude, Aircraft & Instrument status
- Aircraft Launch (06:30)
- In-flight Com / data feed
 - Data downlink from aircraft; data upload from ground
- Aircraft Recovery (11:30)
- Post-flight Aircraft & De-brief (12:30-15:30)
 - Observations, Aircraft & Instrument status, weather for next flight
- Prep for next flight (complete by ~19:00)

Primary Campaign: Data usage



Verify icing conditions envelope for engine development, testing & certification

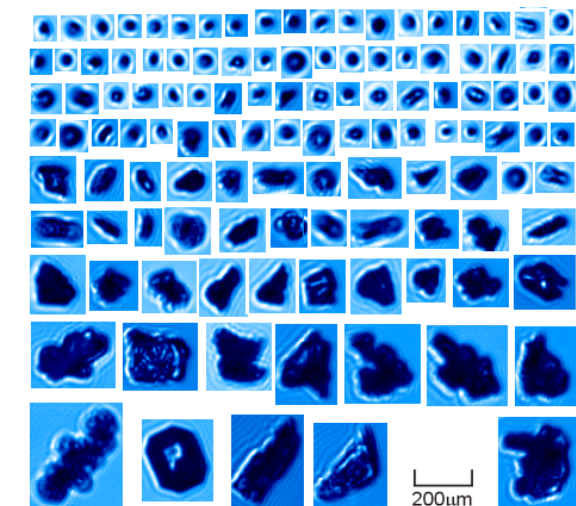
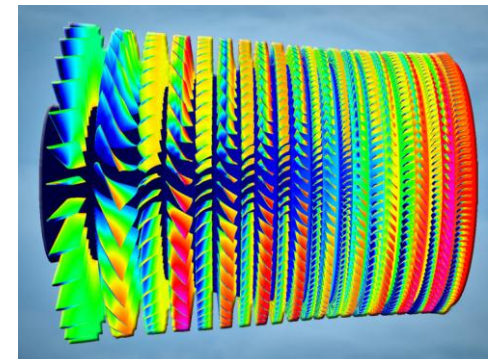
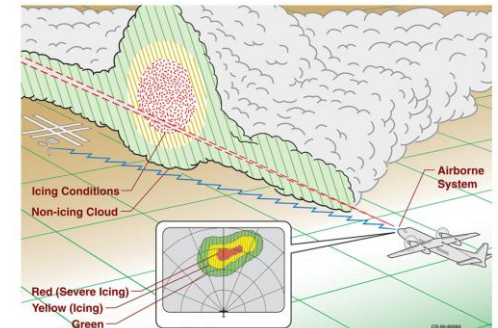
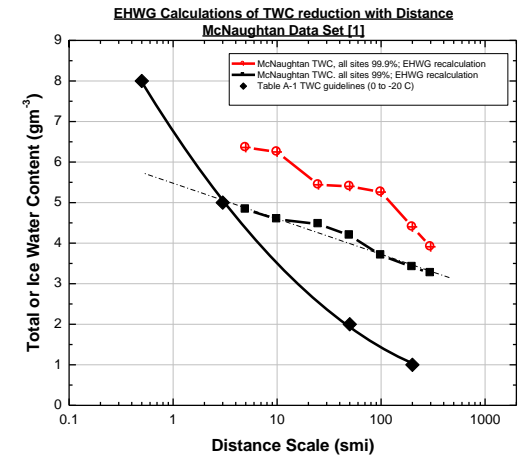
Parameterize inputs for ground-based simulations (experimental/analytical)

Develop Forecast & Nowcast products

Develop detection methods for detect & exit or avoidance

Improve understanding of microphysical properties of deep convection

Validate ground & satellite remote sensing for High IWC



Summary

- Engine power-loss events hypothesized to be caused by large concentration of ice particles near deep convection
- Gov't/industry group identified the need for flight campaign to characterize the environment to enable improved engine designs and detection methods for in-service
- Multi-national, collaborative team is established to perform flight campaign
- Trial flight campaign in Darwin in 2012
- Primary flight campaign in Darwin in 2013



Environment
Canada



FTA
Flight Test Associates, Inc.



**Federal Aviation
Administration**

